Mediterranean Geoscience Reviews (2020) 2:267–281
https://doi.org/10.1007/s42990-020-00023-8

ORIGINAL PAPER

Identifying the Brazil nut effect in archaeological site formation processes

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Received: 14 November 2019 / Revised: 6 March 2020 / Accepted: 26 March 2020 / Published online: 8 April 2020

Abstract
The Brazil nut effect (BNE) is a physical phenomenon by which large granular particles (i.e., archaeological artifacts) in a bed of small disturbed particles (i.e., soil), rise to the top surfaces. This paper examines the physical forces acting on archaeological artifacts—scattered on the surface and buried underground—to identify the major elements of site formation processes (SFPs). Combining theoretical advances in archaeology, pedology, granular physics and spectroscopy, we conducted accelerated laboratory tests on seven typical Israeli soils to form a SFP model. We suggest that the SFPs are the result of two opposing and continuous processes: soil coverage of the site started soon after human activity has ceased, and a force(s) that tends to lift buried artifacts up to exposed surfaces, acting in accordance with Brazil nut effect (BNE). The post-burial forces pressuring artifact movement upward are affected by the artifacts' density and size, soil characteristics and the local environment. As a result, some archaeological artifacts reach exposed surfaces, some are lifted to higher soil deposits but remain buried, and the rest remain in their original burial context.

Keywords Archaeological site formation · Field survey · Brazil nut effect · Soil · Pedology · Granular physics · Spectroscopy

Introduction

Site formation process (SFP): preface

An SFP is any event involving interactions of physical forces, human activity and the environment that affect the characteristics of the archaeological record (Sullivan and Dibble 2014). An understanding of SFPs is obligatory for any rigorously assessed scientific reconstruction of the cultural past. As such, SFPs belong among the core concepts of any archaeological inquiry (e.g., Schiffer 1987, 2010; Karkanas and Goldberg 2018). Controlling for the impacts of SFPs is crucial to the discipline because archaeologists use the patterns of artifact dispersal in the ground to infer behaviors (Stein 2001). One of the major challenges, therefore, is the identification of patterns that are created by ancient behaviors as opposed to those created by later cultural and natural processes. In this respect, one of the major research avenues in the study of SFPs deals with post-depositional and recovery processes (e.g., Schiffer 1972, 1983, 1985; Clarke 1973; Sullivan 1978). According to O'Shea (2002: 212), post-depositional theory is concerned with what happens after an object has left the systemic archaeological context; whereas, recovery theory is concerned with how the actual process of archaeological discovery and recovery can distort or bias the perception of the archaeological record. After several decades of intensive research in these areas, however, the basic physics of the forces impacting scattered archaeological remains on and under the surface remains surprisingly understudied.

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The archaeological aspects

One of the major pillars of archaeological investigation is the field survey: searching for sites and collecting information about the location, distribution and organization of past human cultures across a large area (e.g., Schiffer et al. 1978;

Bintliff and Snodgrass 1988; Banning 2002; Tartaron 2003; Bintliff 2014; Banning et al. 2017). Surface surveys are often complementary to excavations, with the advantage of being less expensive and minimally disruptive (Faust and Katz. 2012; Shai and Uziel 2014). From the spread of artifacts on the surface and their quantitative and typological analysis, the settled areas and relative populations in different prehistorical and historical periods are estimated (e.g., Broshi and Finkelstein 1992; Postgate 1994; Finkelstein 1996; Bintliff and Sbonias 1999; Osborne 2004; Chamberlain 2006). Despite a large range of geomorphic factors, such as the processes of alluviation or colluviation, environmental disturbances (cryoturbation or bioturbation) and developmental processes (e.g., ploughing), the validity of the surface survey for locating archaeological sites has been proven on numerous occasions. For instance, in the archaeology of the southern Levant, this is evidenced in the numerous rescue surveys performed along the route of the Cross-Israel Highway before its construction (Dagan 2010), which correctly attested 125 new sites. Nevertheless, a number of sites were not located during the surface survey, and were only eventually discovered in the course of construction activities or during different stages of salvage excavations (Dahari and Ad 1998). Inconsistencies such as these have been noted in both Israel (e.g., Dagan 2009; Garfinkel and Ganor 2010) and worldwide (e.g., Whallon 1979; Alcock and Cherry 2004; Wossink 2009: 46–48; and references therein). The reasons for these discrepancies have never been properly analyzed or understood.

The other side of the same coin with regard to SFPs concerns the presence of artifacts from earlier levels in the later levels of multi-period and multi-stratum sites (archaeological tells) (e.g., Villa 1982; Finkelstein and Zimhoni 2000). This well-known phenomenon is usually considered to be related to subsequent construction activities, which utilized materials (such as mud) that introduced earlier artifacts into later strata, to differences in erosion between different parts of the site, or to mole rat activity (Sapir and Faust 2016). This may be so and indeed, there are many additional components that may affect SFPs. Nevertheless, before one embarks on clarifying particularities such as these, it is essential to understand the basic physics and dependencies underlying the accumulation of artifacts from different periods on the surface or at boundaries between strata in archaeological sites, and their movements, if any, in different types of soils. Similarly, it is imperative to understand why in certain types of soil, we do not observe archaeological scatters on the surface, despite the presence of archaeological sites beneath.

The physical and geological phenomena

The Brazil nut effect (BNE)

The BNE refers to the phenomenon by which large granular particles, in a bed of small vibrating particles, rise to the top (Fig. 1). The same result occurs with both vertical and horizontal vibrations. Thus, shaking a box of cereal leads to spontaneous ordering of the largest particles toward the upper part of the container, ostensibly against the intuitive assumption that objects will become randomly mixed when jostled. This phenomenon occurs even if the larger particles have a higher density than the smaller ones (Möbius et al. 2001). However, when changing the shaking conditions, the same large particles may sink to the bottom due to what is known as the reverse Brazil nut effect (RBNE) (Breu et al. 2003; Schnautz et al. 2005; Schröter et al. 2006; Garzó 2008). It has also been demonstrated that factors which might at first glance appear inconsequential (e.g., air pressure, starting height, etc.) can change the outcome from a lifting to a sinking. Therefore, these granular systems can be considered out of equilibrium at almost any level (Kudrolli 2004; Shinbrot and Muzzio 2000).

Although these phenomena have long been known and abundantly observed and described (e.g., Williams and Shields 1967; Ahmad and Smalley 1973; Rosato et al. 1987),

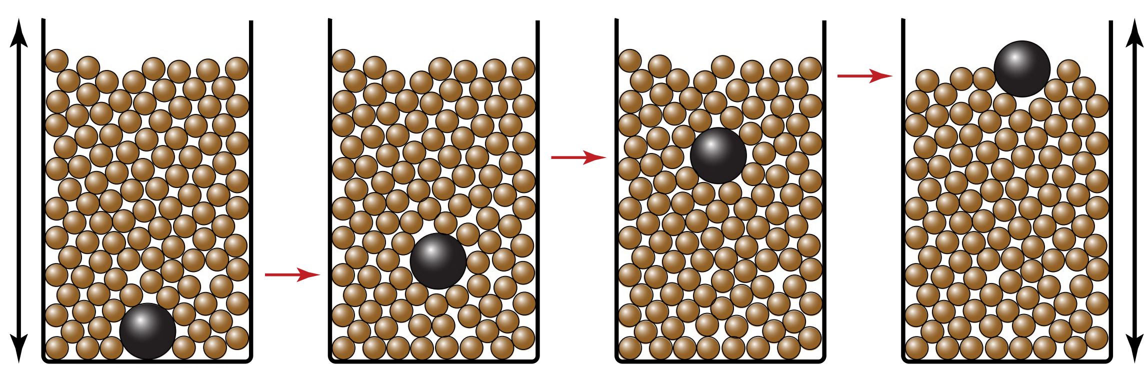

Fig. 1 Simplified representation of the BNE as a result of vertical vibration. Credit: by I. Ben-Ezra

real advances in understanding the physical mechanisms involved have only been achieved in the last two decades (e.g., Möbius et al. 2001; Naylor et al. 2003; Kudrolli 2004; Rémond 2004; Schnautz et al. 2005; Ciamarra et al. 2006; Xu and Zhu 2006; Chung et al. 2013; Wang et al. 2016). The main factors affecting the phenomena are the size ratio (D_L/D_S) (Rosato et al. 2002) and the density ratio (ρ_L/ρ_S) (Möbius et al. 2001) of the large to small particles, where D refers to the diameter; ρ refers to the density; L stands for large object, in our case the archaeological artifact (the intruder); and S refers to the small media, in our case the soil (and see below).

Today, studies of the BNE and RBNE are at the forefront of granular physics, with their implications for early planet-formation processes and the formation of asteroids (Güttler et al. 2013; Matsumura et al. 2014; Perera et al. 2016). Recently, it has been suggested that riverbed armoring, which prevents excessive erosion, should also be seen as an example of a granular segregation phenomenon within the framework of the BNE, where gravel riverbeds typically have an “armored” layer of coarse grains on the surface, which acts to protect the finer particles underneath from erosion. The term “armored layer” has been coined by researchers to describe a situation in which the larger particles can be seen as an armor that protects the riverbed underneath from erosion (Ferdowsi et al. 2017). It had previously been assumed that only fluid mechanics control this pattern, where the river water would wash away the finer particles, leaving the larger particles behind. Experimental results, however, suggested that some riverbed armoring may be due to the granular segregation that follows the BNE from below—rather than fluid-driven sorting from above (Ferdowsi et al. 2017; and see further Seil et al. 2018; Dudill et al. 2018).

Desert pavements (DP)

The presence of rock fragments in topsoils is well known (Poesen and Lavee 1994). According to Poesen’s (1990) estimations, these soils are widespread, particularly in the Mediterranean area where they often constitute more than 60% of the land. In some cases, rock fragment contents in the topsoil are attributed to intensive cultivation. Bruder (1982) described the emergence of large stones each year from the soil of agricultural fields in northern Israel following harvest. Similar patterns for the emergence of surface rock fragments following tillage erosion have been reported from other locations, such as southern Spain (Poesen et al. 1997). The same observation applies for archaeological artifacts, where the fresh ploughing of a fallow field brings to the surface considerable quantities of new archaeological material (Tartaron 2003). It seems, however, that in many cases, the main mechanism underlying the creation of surface rock pavements may be related to the process of DP formation. DP is the final stage of a very long geological/pedological process occurring in what is typically known as reg (desert) soils. The typically described DP formation process includes gravel shattering and fragment lifting in the lower, so-called B horizon, the fragments’ penetration into the upper Vesicular horizon, and finally, their accumulation as a DP on the surface (Amit et al. 1993; Poesen and Lavee 1994). Amit et al. (1993) suggest to separate the long-term shattering process, in the deep soil into five stages in which the shattering rate turns from logarithmic to asymptotic, thus, most of the shattering process takes place in the first stages in the ground. In other studies (e.g., Grotzinger and Jordan 2010), the DP process is limited to the Vesicular horizon, near the upper surfaces. In that case, the lifting process includes the effect of a wind blowing fine-grained material, rain events during which the microbes living underground produce bubbles that raise the pebbles.

DP has also been reported for many types of rocks and morphological surfaces, such as alluvial fans, basaltic flow, pluvial lake beaches and plain terraces, as well as volcanic structures (e.g. Amit et al. 1993; Al-Farraj and Harvey 2000; Valentine and Harrington 2006; Kianian 2014). DP vertical rising on a continuously thickening sedimentary layer have been assumed to be stable landforms. However, recent works (Dietze and Kleber 2012; Dietze et al. 2012, 2013, 2016; Derkum and Dietze 2019) suggest a further lateral process that possibly indicates desert pavements to be a dynamic rather than a stable landform. The proposed mechanism: rain water infiltration causes soil air pressure to increase, as air cannot escape through the mixture of wet clay and sand surface but through the still dry patches below stones, it lifts stones parallel to the slightly inclined surface. Another model suggests that deposition of wind blown sediments is the major agent of pavement evolution and formation and, accordingly, these pavements are actually borne at the surface (Wells et al. 1995). This model, however, is not applicable for all cases of DP formation as it has been tested only for lava flows in specific locations.

Archaeological pavement (AP)

Subsurface redistribution processes resulting in upward and downward movement of artifacts have been well attested to, primarily in the field of prehistoric archaeology (Staurset and Coulson 2014, with further references). Villa (1982: 287) observed that "considerable vertical movement can occur in the absence of visible traces of disturbance. Such displacement—which may be either postdepositional or contemporaneous with the time of burial—alters the original stratigraphic relationships of archaeological items and creates false stratigraphic associations." According to her, layers and soil should be considered as fluid, deformable bodies through which archaeological items float, sink, or glide. The main forces behind these movements are routinely described not only in terms of biogenic activity, but also by other instances, such as differential stresses in the Aeolian soil column due to consolidation, or due to the wetting and drying of sediments that may cause vertical descent of artifacts into the soil (e.g., Cahen and Moeyersons 1977; Moeyersons 1978; Wood and Johnson 1978; Rowlett and Robbins 1982; Villa 1982; Villa and Courtin 1983; Erlandson 1984; Hofman 1986; Bocek 1986; 1992; Bollong 1994; Leigh 1998; Bueno et al. 2013; Araujo 2013). To deal with this vertical mixing of archaeological deposits, a series of mathematical models, based on assigning probabilities to a variety of artifact specimens' movements between discrete stratigraphic layers, have even been developed (Brantingham et al. 2007). All of these explanations and models, reliable as they are, do not take into account additional major forces that are physical in nature and that, in our view, will have a large effect on any given SFP.

We would like to introduce a new term, "archaeological pavement" (AP), describing the physical process by which archaeological artifacts are lifted by the soil and accumulated on open surfaces, indicating, in most cases, a hidden archaeological site below. The term AP is derived directly from its resemblance to DP appearance on the surfaces. In the following, we suggest that the primary force creating AP is the BNE. Similarly, the forces responsible for the RBNE may explain the phenomenon of reverse archaeological pavement (RAP). This hypothesis enables the use of theoretical and experimental results attained from studies of the BNE to enhance our physical understanding of the lifting process of artifacts in archaeological sites through AP formation.

In what follows, based on laboratory tests, we offer a new SFP model that takes into consideration two opposing and continuous processes: soil coverage of the site soon after human activity has ceased, and a force(s) that tends to lift buried artifacts up to exposed surfaces, acting in accordance with Brazil nut effect (BNE). The model will also address the following questions: (i) why even intensive field surveys occasionally fail to detect significant archaeological sites buried in the ground, and (ii) how we can integrate, in the same model, both the lifting process, BNE that leads to AP and its reverse action, RBNE that leads to RAP?

Methods

Seven typical Israeli soils (as defined by Ravikovitch 1981) from different locations (Fig. 2), were tested for their lifting speed using vertical and horizontal vibrations with the same spherical intruder. Yaalon (1997) demonstrated that all terrestrial soils in the Mediterranean region are affected by the addition of Aeolian dust. This activity started when the Sahara became a desert. Hence, values of up to 50% Aeolian material in limestone soils are reasonable (Yaalon and Ganor 1973). This leads to the existence of a high percentage of small-sized particles in local Israeli soils, enhancing the role of the void-filling mechanism.

Out of seven samples, two samples were collected from sites in which a very close correlation was found between the surface survey and the final excavation results. In other words, the archaeological remains from a number of periods collected during the surface survey and from the buried archaeological strata beneath it were almost a perfect match. The first sample (Table 1: No. 2) came from Tel Hadid (Brand 1998); the second sample (Tables 1: No. 3) was from Tel Ras Abu-Hamid (Shavit and Wolf 2008), both located in the upper Shephelah—a lowland region in southcentral Israel stretching over 10–15 km between the mountains and the coastal plain.

Two other samples were taken from sites in the Shephelah, but from slightly different geomorphological locations, which showed a poor correlation between the surface survey and the following excavation. The first sample (Table 1: No. 4) came from Horbat Petora (north). Here, the archaeological surface survey only revealed remains from the Byzantine period; whereas, the following salvage excavation revealed extensive remains from several earlier periods, namely Neolithic, Chalcolithic, Early Bronze I and Roman periods (Gorzalczany and Baumgarten 2005). The second sample (Table 1: No. 1) came from Shoham. This area had been covered by several surveys (Dagan 2010), all of which failed to find any remains of the extensive archaeological site that was found later by accident. The site yielded substantial remains, attributed to eight different periods, namely Late Iron Age/Early Persian, Early and Late Hellenistic, Early Roman, Byzantine, Early and Late Islamic and Medieval periods (Dahari and Ad 1998). Other soil samples (Table 1: Nos. 5–7), with no correlation to attested archaeological remains, were taken for comparative purposes, demonstrating different lifting speeds for additional soil types.

In the first stages of this study, we focused on choosing the best vibrating conditions and selecting the specific artifacts (intruders) to be tested. First, a 2D symmetric loom weight was examined. As this object was not lifted in a horizontal manner during the lifting process, it was difficult to detect the exact moment at which the object was completely separated from the soil. Therefore, a spherical intruder was selected instead, as in this case the completed lifting process is clearly indicated by the roll of the intruder on the surface of the sample. The "lifting time" for the intruder was defined as the time, in seconds, needed for the intruder covered, at the center of the vessel, to reach the top surface and to start rolling freely. Since it was not clear whether the horizontal or vertical vibration is the dominant factor in archaeology, we decided to test all of the samples using both vibrating

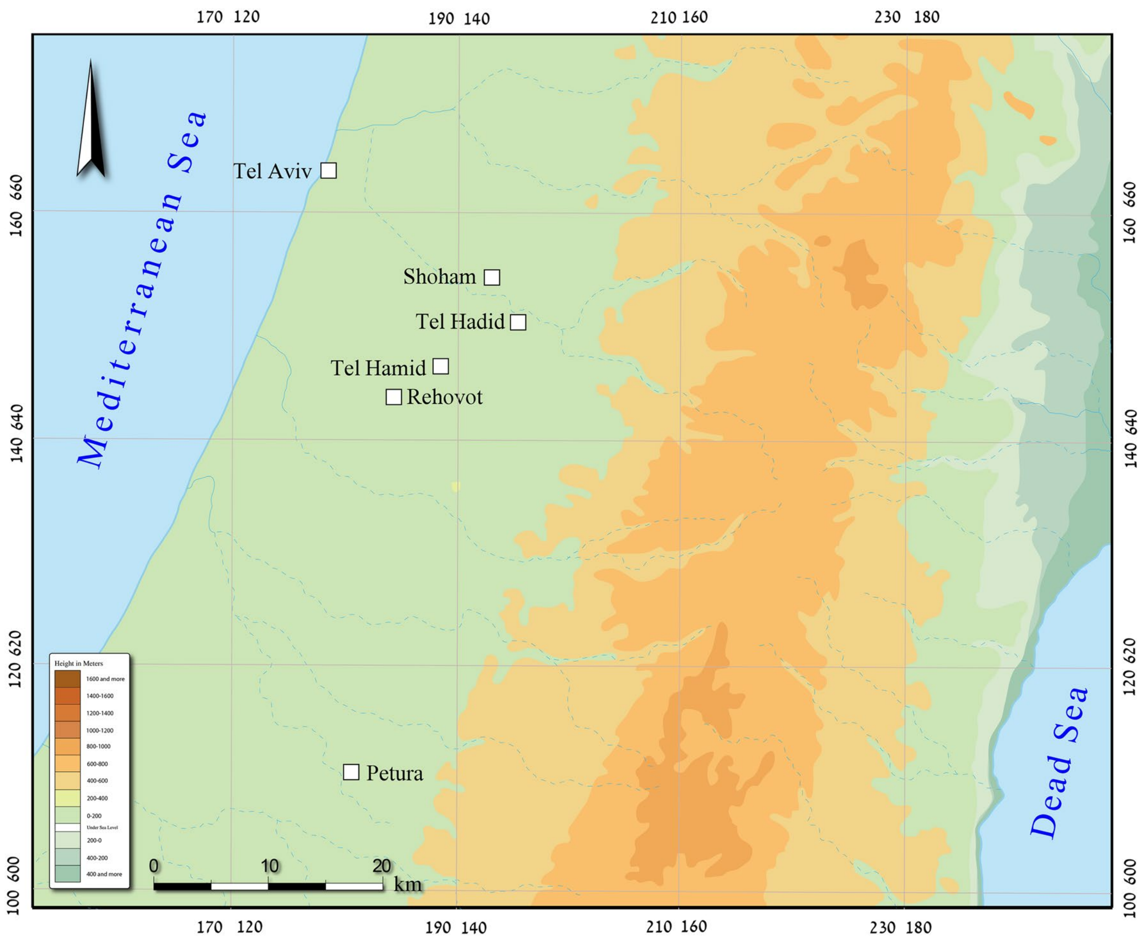

Fig. 2 Map of an area with archaeological sites mentioned in the text. Credit: by I. Ben-Ezra

Table 1 Correlation between field surveys and archaeological excavations for the tested soil samples

Soil sample	Soil type	Location	Correlation between field survey and archaeological excavation
1	Brown alluvial and rendzina soils	Shoham	Very poor The survey failed to find any remains while excavations revealed a multiperiod archaeological site
2	Mountain rendzina soils	Tel Hadid	Very good The survey results corresponded to the excavation results
3	Mediterranean brown forest rendzina soils	Tel Ras Abu-Hamid	Good The survey results corresponded in major part to the excavation results
4	Brown steppe soils	Ḫorbat Petora	Poor The survey results revealed remains from one period while excavations revealed a multiperiod archaeological site
5	Costal sand dunes	Tel Aviv	Not applicable
6	Brown–red sandy soils (hamra)	Rehovot	Not applicable
7	Desert stony land	Timna 34	Not applicable

directions, applying the same vibrating characteristics and using the same object as the intruder.

The preparation procedure of the soil samples and the final protocol of running conditions are as follows:

1. The soils were sampled in the locations described above, after removing ca. 10 cm from the topsoil.
2. The samples were sieved in a screen of 2 mm: to receive a clean material.
3. The samples were heated in an oven at the temperature of 180° C for 60 min to achieve same dry conditions.
4. After the heating, the samples were stored in closed vessels to prevent absorbing the external moisture.
5. Before vibration each sample was mixed in its storing vessel for two minutes to avoid soil's compaction (cf. Grotzinger and Jordan 2010: 129–130).
6. Device: a versatile horizontal and vertical vibrator was used. The dimensions of the conical–cylindrical vessel used to hold the samples were: bottom diameter 93 mm, top diameter 105 mm, height 72 mm (Fig. 3).
7. Intruder: a spherical intruder with a diameter of 14.3 mm and density of 0.72 g/ml^3.
8. Prior to the tests, the intruder was installed below the surface at the center of the holding device to minimize the effect of the walls and of soil's cycling (cf. Yaalon and Kalmar 1978).
9. Running conditions in both horizontal and vertical vibration: lifting distance for measuring the lifting time, 16.3 mm; frequency 5.92 Hz; amplitude 14 mm.

Soil has unique spectral characteristics, which allow for quantification of organic matter, clays, hygroscopic water, crystalline iron, calcite, etc. (Stoner et al. 1980; Nocita et al. 2015; Viscarra Rossel et al. 2016). Thus, despite it being a very complex matrix (Holliday 2004; Grotzinger and Jordan 2010), the soil's spectral characteristics can simplify its complexity and indicate its characteristics (Ben-Dor et al. 2007, 2017; Viscarra Rossel and Bouma 2016). The samples were measured using Tel Aviv University's protocol (Ben-Dor et al. 2008, 2015), concentrating on three parameters: sand (particle size 2.0–0.05 mm), silt (particle size 0.05–0.002 mm) and clay contents (particle size less than 0.002 mm) that appear to be essential to the lifting and sinking speeds of artifacts (Rosato et al. 2002).

Results

During the laboratory testing, two samples from the sites (Tel Hadid and Tel Ras Abu-Hamid) in which a very close correlation was found between the surface survey and the final excavation results have demonstrated relatively short lifting speed/time for the buried object toward the surface, 10 and 14 s, respectively, under horizontal vibration and 12 and 21 s, respectively, under vertical vibration (Table 2: Nos. 2–3, respectively).

Two other samples from the sites which showed a poor correlation between the surface survey and the following excavation (Horbat Petora and Shoham), have demonstrated comparatively long lifting speed/time for the buried object toward the surface, 17 and 72 s, respectively, under horizontal vibration and 23 and 49 s, respectively, under vertical vibration.(Table 2: Nos. 4; 1, respectively).

The results from both vibration modes (Table 2) demonstrated a close similarity in the order of the lifting speeds, and in the mean lifting velocity (12.4 and 14.5 mm/s × 10, respectively), despite the large qualitative variety of the results (V_{max}/V_{min} in the horizontal vibration was 15:1 and in the vertical vibration 6:1).

The principal results were that the faster the lifting speed of each examined soil, the closer the correlation between the survey results and the excavation results, and vice versa (Figs. 4, 5). This discovery has important consequences for the theoretical understanding of the SFP at any archaeological site.

The results of spectral investigation for all seven samples are presented in Table 3. The correlation found

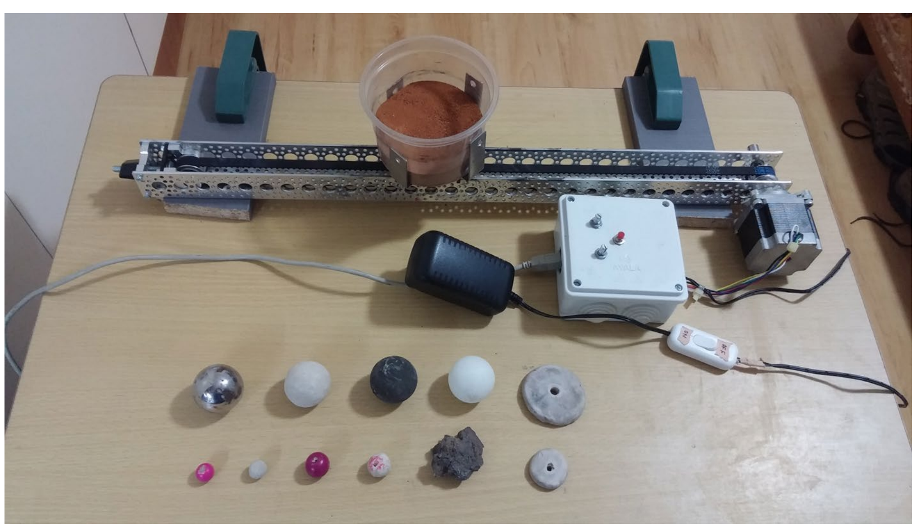

Fig. 3 The experimental device with a soil sample and various tested intruders. Credit: by D. Luria

Table 2 Comparison of the lifting time and speed of the soil samples under horizontal and vertical vibrations

Soil sample	Horizontal vibration				Vertical vibration			
	Mean lifting (s) and number of tests (#)	Speed (V) (mm/s × 10)	STD_t	STD_v	Mean lifting (s) and number of tests (#)	Speed (mm/s × 10)	STD_t	STD_v
1	72 (12)	3.2	41.8	1.8	49 (10)	3.8	16.4	1.4
2	10 (9)	19.8	5.1	7.8	12 (7)	14.2	3.3	3.6
3	14 (9)	13.9	6.7	4.9	21 (10)	9.3	9.5	3.9
4	17 (7)	9.7	3.1	1.8	23 (10)	8.4	8.6	3.7
5	7 (10)	25.3	2.6	7.8	7.5 (6)	21.8	0.5	1.5
6	6 (6)	27.7	0.8	3.8	9 (6)	18	1.3	2.5
7	105 (6)	1.7	26.6	0.37	68 (10)	3.6	38	2.4
Mean values	33	14.5			34.1	12.4		
V_{Max}/V_{Min}		15:1				6:1		

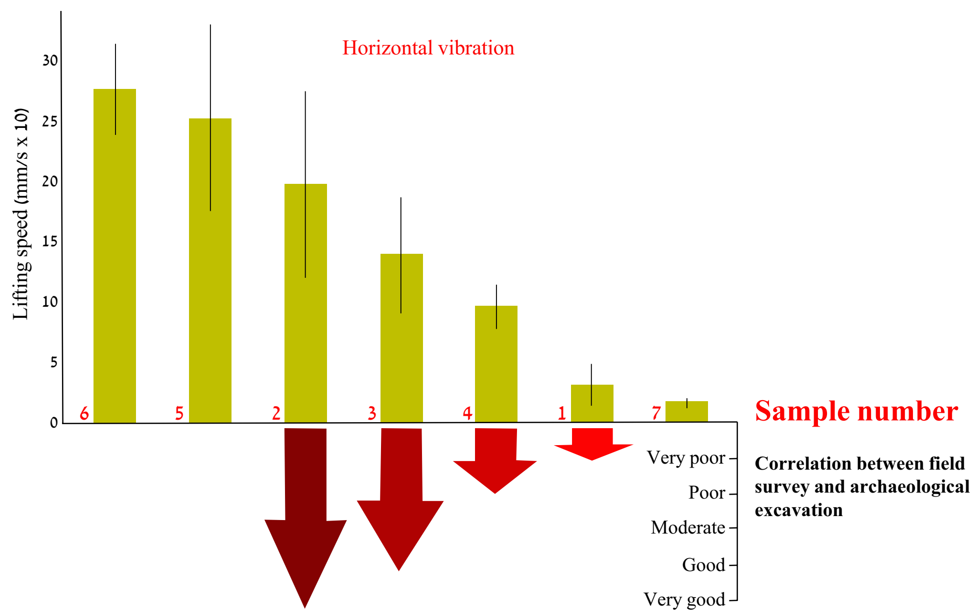

Fig. 4 Horizontal vibration case. Graphical comparison of lifting speeds and the correlation between field surveys and the subsequent archaeological excavations, where available. Credit: by D. Luria and I. Ben-Ezra

between lifting speed and sand and silt contents is shown in Fig. 6a, which demonstrates that an increase in the amount of large-size particles (sand) decreases the lifting speed. In contrast, increasing the amount of small-size material (silt), as shown in Fig. 6b, increases the lifting speed. Both findings are in accordance with the BNE and the void-filling mechanism.

Analyzing the effect of clay content on the lifting speed ended with very poor correlation: in horizontal vibration: $R^2 = 0.3$ and in vertical vibration $R^2 = 0.11$. In this regard, it should be noted that our work was limited to dry conditions; while in real-field cases, clays tend to swell with the addition of water. Thus, their actual size will vary between dry and wet periods and in most cases, they will be significantly larger than under totally dry conditions (Tariq and Durnford 1993).

Discussion

Assuming that the primary force creating AP is the BNE, we adopt principal experimental and theoretical data attained from three leading BNE teams. These results are schematically described in Fig. 7. For simplification, all of these major BNE studies used spherical intruders adopted also in our experiment. Our model for SFP will include the principal results described in Fig. 7b–d.

Möbius et al. (2001) demonstrated that the amount of time taken for spheres of the same diameter but different densities to be lifted from a predetermined depth to the free surface is a function of the specific particle density ratio ρ_{L}/ρ_{S} (artifact/bed media) (Fig. 7a): rising times are smaller at large and small density ratios; whereas, the

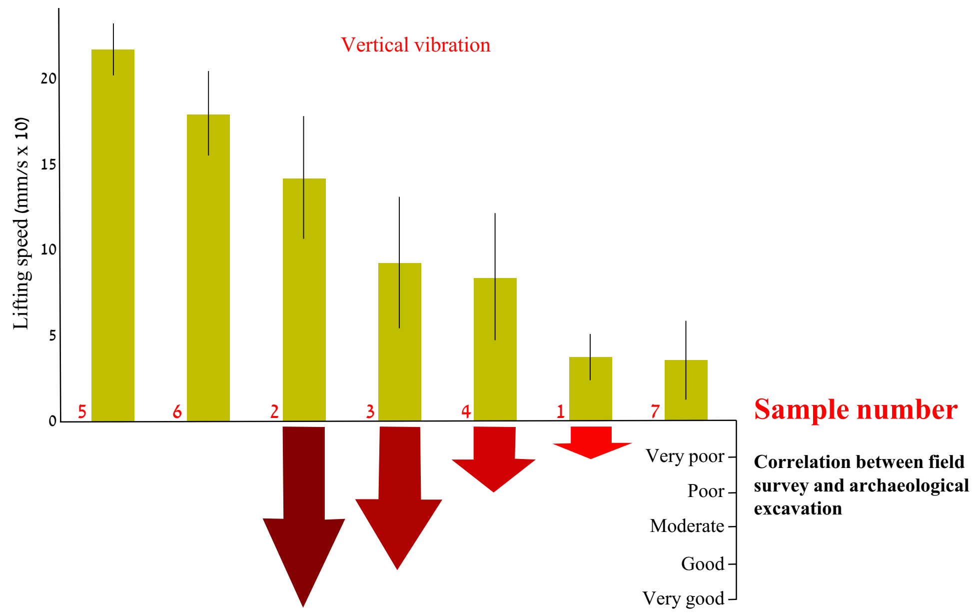

Fig. 5 Vertical vibration case. Graphical comparison of lifting speeds and the correlation between field surveys and the subsequent archaeological excavations, where available. . Credit: by D. Luria and I. Ben-Ezra

Table 3 Lifting speed of the soil samples under horizontal vibration versus values of sand, clay and silt

Soil sample	Speed (V) (mm/s × 10)	Sand (%)	Clay (%)	Silt (%)
1	3.2	32.3	38.8	40.9
2	19.8	31.8	34.4	38.7
3	13.9	27.3	20.6	55.1
4	9.7	34.6	37.4	25.6
5	25.3	22.4	44.8	45.8
6	27.7	16.4	9.9	78.9
7	1.7	48.1	51.3	22.6

Using the proxy analysis for sand, clay and silt, based on the spectral information, result in approximately 5–10% of total error. The benefit of using the proxy analysis even if we have this error is that for clay the error is 5% (most important factor) and it can be measured in the field in real time

rising time for moderate density ratios is larger. The maximum rising time is achieved at a density ratio of around 0.5. However, the most important variable in our work is "lifting speed" and not "lifting time". Therefore, in Fig. 7b, "time" is replaced by "speed", without violating the basic premises of Möbius et al. (2001).

Rosato et al. (2002) demonstrated a direct relationship between the diameter ratio D_L/D_S (artifact/bed particles) and the vertical lifting speed of an object under the BNE (Fig. 7c). A simple explanation for these results is that as the D_L/D_S ratio increases, the smaller spheres can more easily intrude beneath the large particles, thereby increasing the lifting speed. This process is called void filling.

Breu et al. (2003) defined the regimes under which the classical BNE switches to a RBNE, in which the particles

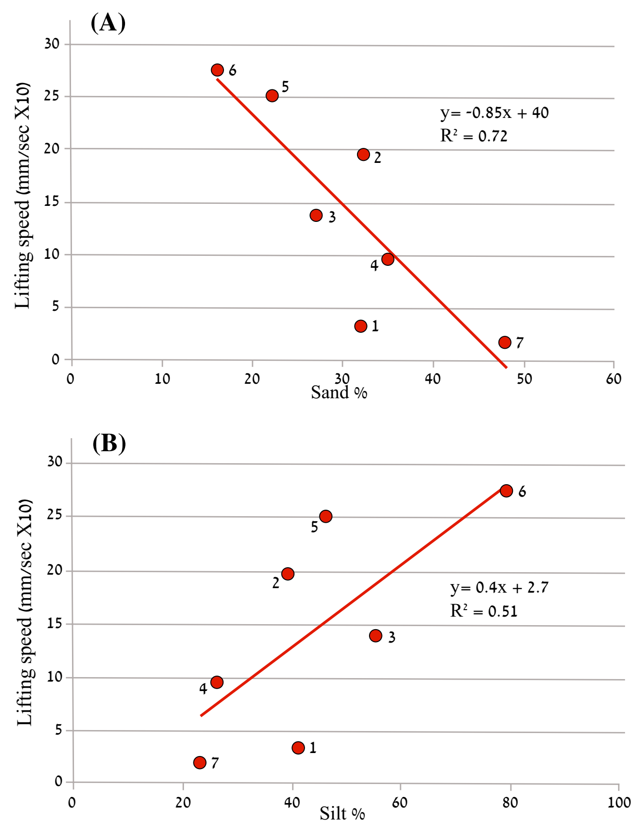

Fig. 6 Correlations between lifting speed in horizontal vibration and the contents of **a** sand, and **b** silt. Numbers refer to the samples defined in Table 1. Credit: by E. Ben-Dor and I. Ben-Ezra

move to the bottom (Shinbrot 2004). The results (Fig. 7d) demonstrate that a high diameter ratio and a low particle density ratio may lead to a BNE situation; whereas, a low

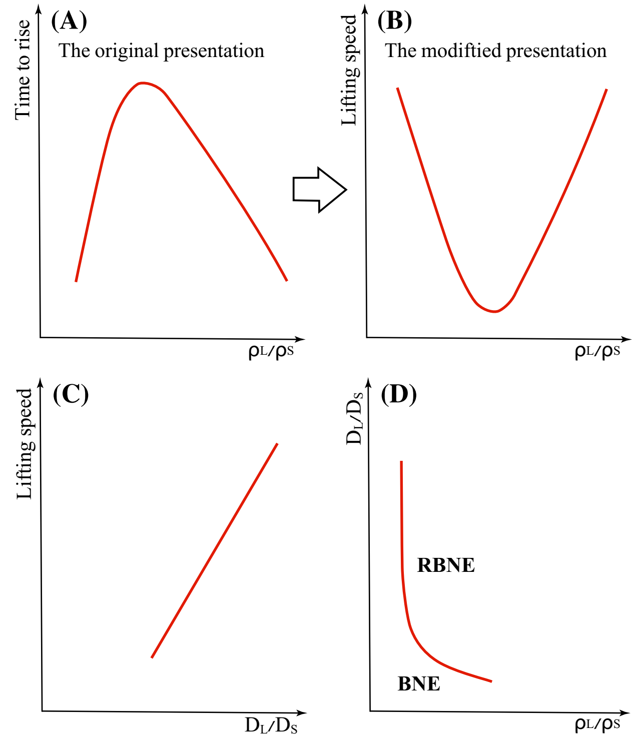

Fig. 7 Schematic effects of variable particle density ratios (ρ_L/ρ_S) and diameter ratios (D_L/D_S) on the lifting speed of spherical objects under the BNE, and transfer from the BNE region to the RBNE region. Credit: by D. Luria and I. Ben-Ezra, modified after Mobius et al. 2001; Rosato et al. 2002; Breu et al. 2003

diameter ratio and a high density ratio will lead to a RBNE condition.

The proposed SFP model

Two new terms are added to the following discussion: "speed of soil forming" and "critical speed". It is assumed that shortly after an active site is abandoned, it begins to be covered by soil at a constant rate. This rate is affected by geographical location, specific topography, wind patterns and other environmental variables. The "rate of soil forming" is the quantity at which the parent material is covered by a new soil. At the same time, a vertical lifting force (BNE) will begin to act upon the artifacts. Artifacts having a lifting speed that is higher than the rate of soil forming will remain on or near the surface. On the other hand, artifacts with a lifting speed lower than that rate of soil forming will move upward through the new soil cover, but will never reach the open surface—as long as the two separate processes, covering and lifting, are not disturbed or changed. The point at which the specific lifting speed equals the rate of soil forming is defined here as the "critical speed".

Figure 8 presents the theoretical lifting speeds of two different soils—"fast" and "slow"—while assuming an

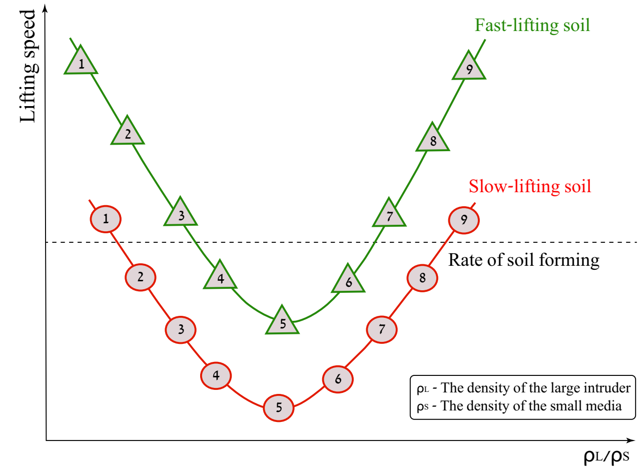

Fig. 8 Lifting speeds of fast and slow soils. Credit: by D. Luria and I. Ben-Ezra, based on modification of the results presented by Möbius et al. 2001

equal rate of soil forming. As a pure theoretical exercise, each soil contains the same nine artifacts.

Following the original results of Möbius et al. (2001), while at the same time considering the process of soil forming, we arrive at the following outcomes: in the slow-lifting soil, only objects 1 and 9 will reach the open surface as their speed is higher than the "critical speed". On the other hand, in the fast-lifting soil, objects 1, 2, 3, 7, 8, and 9 will be fully lifted. Concurrently, the slower objects will also be lifted according to their individual speeds, but they will not reach the topsoil.

Figure 9 presents a model of a site formation composed of fast lifting soil and two archaeological levels. The artifacts (Nos. 1–9) shown here are the same as artifacts described in Fig. 8. Thus, Fig. 9a displays the situation after level 2 has fully developed and before level 1 has begun to accumulate. Level 2 also includes heavy and large objects that will sink to the bedrock by RAP. Figure 9b exhibits the situation after level 1 has fully developed. Theoretically, if a field survey is performed after level 2 has been fully covered (Fig. 9a), artifacts 1, 2, 3, 7, 8, and 9 will be found; whereas, if the field survey is performed after level 1 has fully developed (Fig. 9b), artifacts 1, 2, 3, 7, 8, and 9 from both levels will be found, but not artifacts 4, 5, or 6 from either level. The latter objects might be revealed only through shovel or probe tests. This theoretical description also shows that the slowest artifact of level 2, artifact 5, is still located in the covered soil of level 2; whereas, artifacts 4 and 6 have already crossed to level 1.

Figure 10 describes the same situation as in Fig. 9, but with slow-lifting soil. In this case, a field survey performed after level 1 or 2 has fully developed will reveal only artifacts 1 and 9 of both levels.

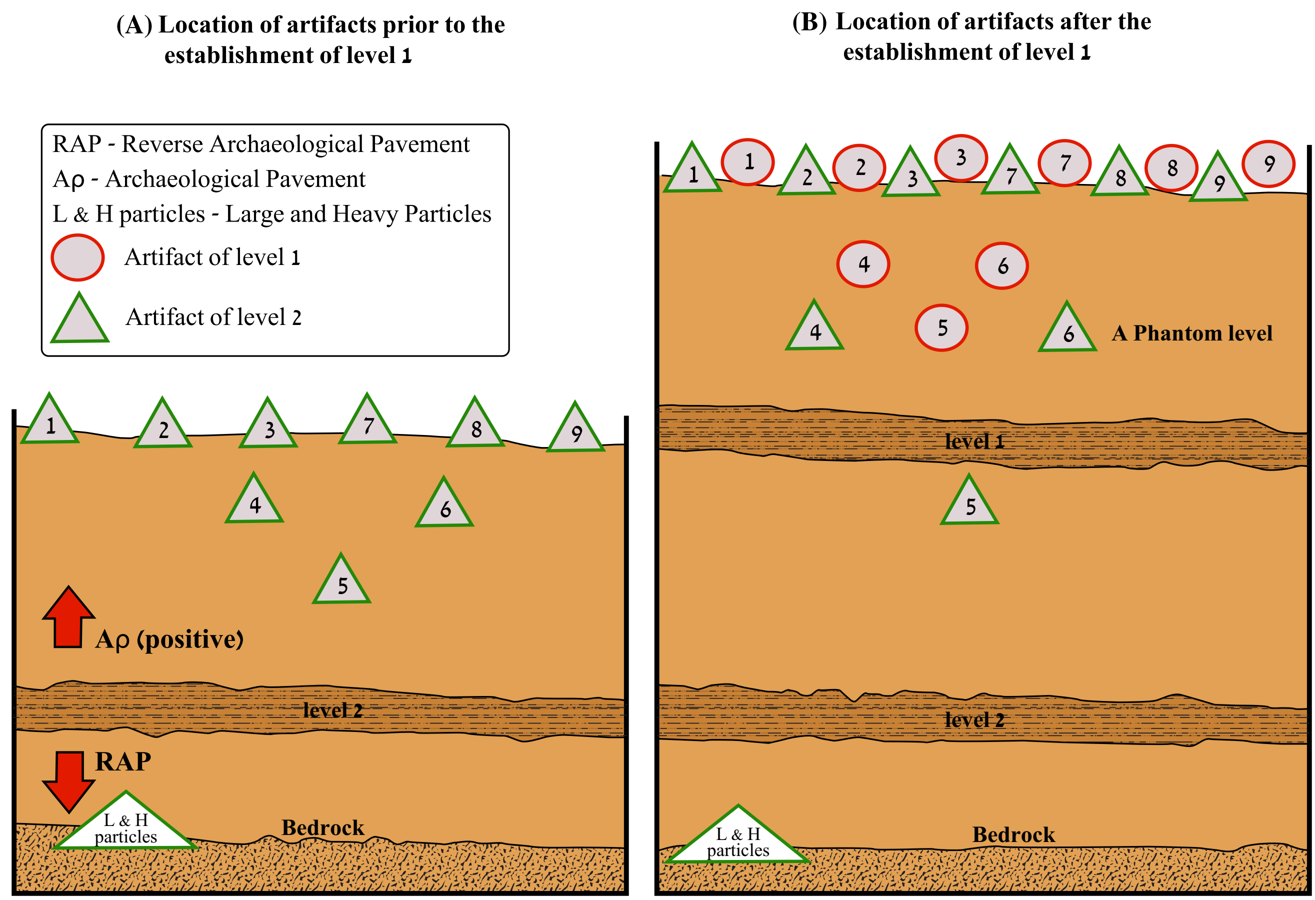

Fig. 9 The establishment of an archaeological site by fast-lifting soil. Credit: by D. Luria and I. Ben-Ezra

Under more extreme situations, such as when the soil is extremely slow-lifting, only a few or no objects will reach the open ground and even a careful survey might fail to find archaeological remains. This might explain the case of sample No. 1 from Shoham (Table 1), located in an area that was covered by several surveys, all of which failed to find any remains of the buried archaeological site. The above discussion follows the theoretical consequences derived from Fig. 7b only. In addition, Fig. 7c deals with lifting speed versus diameter ratio which also affects artifact's lifting. However, as Fig. 7c has the same right-hand side characteristics of Fig. 7b (i.e., by replacing "density ratio" with "diameter ratio"), the SFP model that would be derived from Fig. 7c will be, qualitatively, the same as the one derived from Fig. 7b. Thus, to avoid redundancy, the SFP results for Fig. 7c are not presented.

A few scholars in the Southern Levant have tried to use shovel testing (Portugali 1982; Shott 1985; Leibner 2009; Faust and Katz 2012; Shai and Uziel 2014), or even boreholes, to enhance the results of the surface survey conducted for tells prior to their excavation. This procedure (more common in North America) which usually consists of digging a random number of pits scattered on the tell's surface to a depth of ca. 20–30 cm provides important complementary information to the results obtained from the surface surveys. Deeper probe tests are intended to be dug from the surface until a buried site is reached. The outcomes of the shovel and probe tests enable to improve statistical indications of the quantitative and qualitative traits of the remains buried underground, as described in Figs. 9 and 10.

Vertical movements of the various artifacts, having different propagation speeds, may produce unexpected results:

(i) Fig. 9b: after level 1 is formed and starts to be covered, objects 4 and 6 of level 2 penetrate into level 1 and continue to be lifted by the soil of level 1. At the same time, object 5 of level 1, having the lowest lifting speed among the artifacts, is also lifted. At some point, object 5 from level 1 reaches the same height position as that of objects 4 and 6 from level 2. If an archaeological excavation is performed at that time, the three objects, originating from two different levels, might be considered a "new" level. We term this situation a "phantom level".

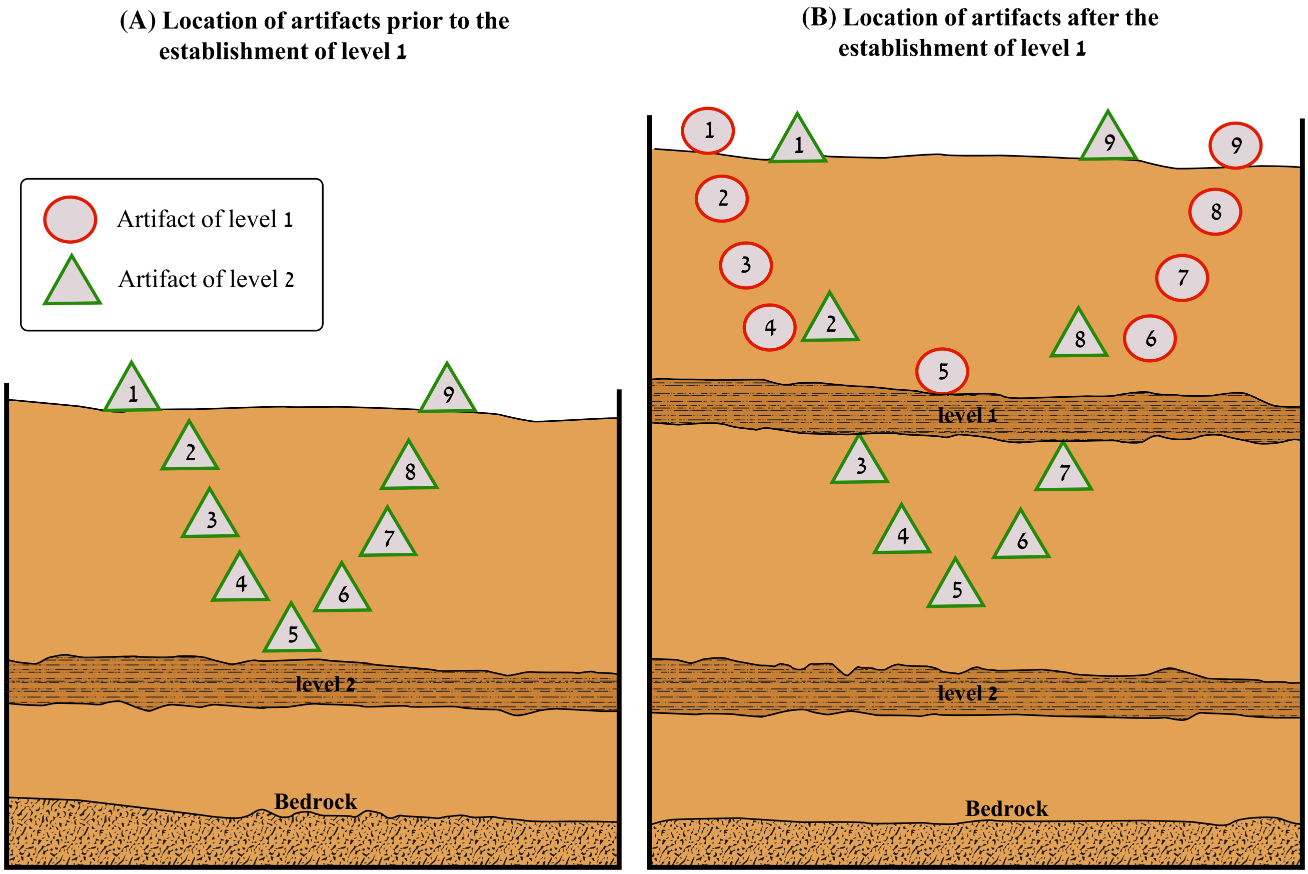

Fig. 10 The establishment of an archaeological site by slow-lifting soil. Credit: by D. Luria and I. Ben-Ezra

(ii) Assume, ostensibly, a "stratum" containing artifacts with the same lifting speeds, which are less than the critical speed—for example, objects 4 and 6 shown in Figs. 9a and 10a. This "stratum" might be considered a separate level in an archaeological excavation and it is defined here as an "induced level".

Interestingly, almost four decades ago, Villa (1982: 266, 278) had already reported similar empirical observations, without being able at that time to relate them to any physical explanation:

> I realize that the conclusions I have drawn may be called into question [...] that layer boundaries through which objects seem to have moved may have existed only in the mind of the excavator who was too zealous in defining bedding planes, stratigraphic boundaries, and living floors. Whatever processes may have caused vertical displacement of artifacts—so the reasoning goes—we would expect layer boundaries to be blurred. This would immediately suggest to experienced eyes some degree of mixing. We know now that disturbance during burial or following deposition may affect archaeological assemblages to a much larger extent than previously imagined, and that considerable vertical displacement of artifacts (both upward and downward) may occur even when the matrix itself has not been visibly disturbed or displaced.

In view of this, it is clear that a surface survey performed on slow-lifting soils will underestimate portions of the potential artifacts or will even ignore a site's artifact assemblage entirely, with the only alternative to locating them being the use of shovel or probe tests. In addition, it follows that frequent surveys conducted in the same area will tend to "dilute" the archaeological remains and will lead to a gradual degradation of later results. Banning (2002: 220) correctly identifies the effect of numerous surveys performed in the same area as "exhaustion" (contra to Faust and Katz 2012, who consider the archaeological survey to be a non-destructive procedure). Therefore, it is advisable that all past and present surveys conducted in the same area be integrated into a single cumulative databank. Using the same physical rationale discussed above, even the shovel tests cannot be considered to give "true" results (contra to, e.g., Leibner 2009: 68), against which the accuracy of the field survey can be assessed, but rather partial and mostly of the slow lifted objects.

It should be emphasized that in addition to the BNE phenomenon, there are numerous other soil's activities that can cause lifting or mixing of artifacts in archaeological record (see above). For instance, bioturbation of archaeological remains can occur due to burrowing, particularly by rodents, earthworms, ants or termites (e.g., Stein 1983; Erlandson 1984; Canti 2003; Bueno et al. 2013; Araujo 2013; Więckowski et al. 2013; Sapir and Faust 2016), as well as to manuring and mixing (Wood and Johnson 1978). Bruder (1982) demonstrated a substantial effect of mole activity on the pedoturbation of objects in soil. However, the artifacts lifted by moles are limited in size to at most 30 mm across. Therefore, the overall effect of this type of bioturbation on the lifting characteristics of archaeological artifacts is limited. In this regard, Yaalon and Kalmar (1978) assumption that the uniform content of clay with depth is the result of mixing the surface soil and subsoil during a subsequent wetting and swelling is highly relevant. According to them, the differentiation in the non-clay fraction is due to seasonal wetting followed by uplift of the coarse grains (see also Madsen and Müller-Vonmoos 1997).

In addition, we assume that the forces responsible for the RBNE provide an explanation for the creation of reverse archaeological pavement (RAP). Such instances have been detected in specific archaeological assemblages, without acknowledging the reasons for their occurrence (Ben-Yosef 2010), or without considering the RBNE (Hofman 1986; Staurset and Coulson 2014). The situation, in the former case, relates for instance to specific sites for copper production in Wadi Arabah in southern Israel and the "surprising" deposition of heavy slags (Ben-Yosef 2010: 348, levels 6 and 7; 349, Fig. 5.66b; 350, Fig. 5.67b; 559, levels 9 and 8). In this particular case, it may be assumed that before the earliest periods of copper production, a layer of soil covered the bedrock. During periods of copper production, the produced slags were gradually dumped on this topsoil, but over time, these heavy and large particles descended to the bedrock, where they are observed today, in accordance with the RBNE (for additional instances, see Villa 1982).

Throughout this work, we assume that the SFP is the result of two opposite and continuous processes: the first is coverage of the site by soil and the second is a physical force, or a combination of several forces, leading mostly to raising (and sometimes for sinking) of the artifacts. These forces might be attributed to cycles of temperature, seismic, volumetric or pressure within the soil (see, e.g., Ravikovitch 1981; Cahen and Moeyersons 1977; Claudin and Bouchaud 1997; Madsen and Müller-Vonmoos 1997; Chen et al. 2009). All of these postulates are characterized in producing local perturbations, similar to vibration, which leads to BNE. Therefore, we suggest that the main physical factor leading to the creation of AP is the BNE. This claim is supported by following observations:

1. AP and its diverse direction, RAP, demonsrate the same lifting and sinking characteristics as the BNE and RBNE.
2. The results present in Fig. 6 demonstrate that as the amount of large-size particles (sand) increases in the soil, the lifting speed decreases, and vice versa with regard to small particles (silt). These outcomes are in full accordance with BNE characteristic (Fig. 7c).

Successful correlation of lifting mechanisms with different types of soil and their role in the SFP, identified through soil spectroscopy, will have far-reaching implications for many venues of scientific inquiry. Beyond its obvious value for clarifying the hitherto unacknowledged fundamental physical laws governing the SFP, it will assist in estimating the percentage of artifacts that might still be buried in the ground at different sites. This would significantly reduce the estimation error in the calculation of inhabited areas from different periods at any given site, adding a powerful dimension for demographic estimates of ancient populations. It is important to emphasize that the SFP phenomena are far more complicated than the theoretical and experimental state of the art achieved in studies of the BNE. The main reasons for this are the complex nature of soil, the environmental conditions, and the structure of the archaeological objects. Nevertheless, if we tackle the problem from several interdisciplinary angles, the limitations of predictive modeling can be overcome by adopting the simplifications that are already being used in BNE studies together with the implementation of advanced mathematics and statistical techniques, in particular, statistics for incomplete data and possibly hidden Markov models and Tweedie 2009), in which the system being modeled is assumed to be a Markov chain with hidden variables.

Some methodological notes on further SFP modeling

1. In our simplified model, we assumed that the two main opposite processes affecting the AP are continuous and stable over time. This assumption seems to be valid for long durations. On the other hand, it does not take into account the artifacts with high-speed properties which will tend to concentrate on the topsoil (for instance, artifacts 1, 2, 3, 7, 8 and 9 in Fig. 9, and artifacts 1 and 9 in Fig. 10). In such cases, the lifting forces and covering process will be affected differently in different seasons

of the year by rain, temperature, Aeolian dust, etc. Thus, these high-speed-lifted objects should be assessed differently in different seasons along the year.

2. At this stage, we are considering only the vertical movement. Under real field conditions, one expects horizontal movement as well, in particular, for asymmetrical objects (Hofman 1986).
3. In our model, we suggest that all of the artifacts reaching the outer surfaces of level 2 (Figs. 9–10) will also reach the surface of the mature level 1. This is, of course, problematic under real field conditions, as it requires that during the whole period in which level 1 is flourishing, the artifacts of level 2 will stay unaffected on the open ground and will not be removed. For a more realistic model, one would have to assume that any early layer will be diluted by activities taking place in a newer layer.
4. Based on the above outcomes, it might be supposed that in a multilayer site, dilution of the deepest level will be greatest, while that of the newest level will be the least. This theoretical assumption has been already been detected by Dagan (2010: *32), without acknowledging the real reasons behind this observed phenomenon.
5. It might be assumed that human activities related to the surface (i.e., ploughing and farming) will increase the lifting speed of the artifacts significantly (cf. Bruder 1982; Tartaron 2003). On the other hand, gradual compaction of soil over time (Grotzinger and Jordan 2010: 129–130) might reduce the lifting speed of the artifacts with time.

Conclusions

A new empirical–theoretical model for SFP based on granular physics, pedology, accelerated tests and archaeological observations, was outlined. It is suggested that the AP phenomenon is an external result of the same internal forces responsible for the BNE and the RBNE. At the same time, an opposite process also occurs: a constant and continuous coverage of the site by external soil. These two processes begin just after a site is abandoned, and continue to the present day. They demonstrate different lifting rates for different types of artifacts, soils and outdoor conditions. The experimental work reveals that the faster the lifting rate of a given soil, the better the correlation between the results of the surface survey and the final excavation outcome, and vice versa. Thus, soil type has one of the most important effects on SFPs.

Acknowledgements We are grateful to the many scholars, from various fields of science, who offered their insightful remarks during the preparation of this study, namely, Erez Ben-Yosef, John Bintliff, Mark Cavanagh, Haim Diamant, Israel Finkelstein, Svend Hansen, Gunnar Lehmann, Ephraim Lytle, Isaac Meilijson, Alon Shavit, Phil Sapirstein, Oren Tal, Oded Luria, Elad Luria and Vili Vilensky. That said, any responsibility for the ideas expressed in this manuscript rests with its authors alone.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Ahmad K, Smalley IJ (1973) Observation of particle segregation in vibrated granular systems. Powder Technol 8(1–2):69–75
Alcock SE, Cherry JF (2004) Side by side survey: comparative regional studies in the Mediterranean world. Oxbow, Oxford
Al-Farraj A, Harvey AM (2000) Desert pavement characteristics on wadi terrace and alluvial fan surfaces: Wadi Al-Bih, U.A.E. and Oman. Geomorphology 35:279–297
Amit R, Gerson R, Yaalon DH (1993) Stages and rates of the gravel shattering process by salt in desert reg soils. Geoderma 57:295–324
Araujo AG (2013) Bioturbation and the upward movement of sediment particles and archaeological materials: Comments on Bueno et al. J Archaeol Sci 40:2124–2127
Banning EB (2002) Archaeological survey. Kluwer Academic/Plenum Publishers, New York
Banning EB, Hawkins A, Stewart ST (2017) Quality assurance in archaeological survey. J Archaeol Method Theory 24(2):466–488
Ben-Dor E, Taylor RG, Hill J, Dematte JAM, Whiting ML, Chabrillat S, Somme S (2007) Imaging spectrometry for soil applications. Adv Agron 97:321–391
Ben-Dor E, Heller D, Chudnovsky A (2008) A novel method of classifying soil profiles in the field using optical means. Soil Sci Soc Am J 72:1113–1123
Ben-Dor E, Ong C, Lau IC (2015) Reflectance measurements of soils in the laboratory: Standards and protocols. Geoderma 245:112–124
Ben-Dor E, Granot A, Notesco G (2017) A Simple apparatus to measure soil spectral information in the field under stable conditions. Geoderma 306:73–80
Ben-Yosef E (2010) Technology and social process: Oscillations in Iron Age copper production and power in southern Jordan. Dissertation, UC San Diego
Bintliff JL (2014) Regional survey in the Mediterranean and Near East: a brief history and review of current approaches. In: Arikan Erciyas DB, Sökmen E (eds) Regional studies in archaeology. Ege Yayinlan, Istanbul, pp 1–14
Bintliff J, Sbonias K (eds) (1999) Reconstructing past population trends in Mediterranean Europe, 3000 BC–AD 1800. Oxbow Books, Oxford
Bintliff J, Snodgrass A (1988) Off-site pottery distributions: a regional and interregional perspective. Curr Anthropol 29(3):506–513
Brand E (1998) Salvage excavations on the margins of Tel Hadid: preliminary report. Institute of Archaeology, Tel Aviv University, Tel Aviv
Bocek B (1986) Rodent ecology and burrowing behavior: predicted effects on archaeological site formation. Am Antiq 51:589–603
Bocek B (1992) The Jasper ridge reexcavation experiment: rates of artifact mixing by rodents. Am Antiq 57:261–269
Bollong CA (1994) Analysis of site stratigraphy and formation processes using patterns of pottery sherd dispersion. J Field Archaeol 21:15–28

Brantingham PJ, Surovell TA, Waguespack NM (2007) Modeling post-depositional mixing of archaeological deposits. J Anthropol Archaeol 26:517–540
Breu APJ, Ensner H-M, Kruelle CA, Rehberg I (2003) Reversing the Brazil-nut effect: competition between percolation and condensation. Phys Rev Lett 90(1):014302
Broshi M, Finkelstein I (1992) The population of Palestine in Iron Age II. Bull Am Sch Orient Res 287:47–60
Bruder G (1982) The vertical movement of rocks and flint artifacts on the Yiron Plateau, Upper Galilee. Mitekufat Haeven: J Israel Prehist Soc 17:16–26 **(Hebrew with English Summary, pp. 27–29)**
Bueno L, Feathers J, De Blasis P (2013) The formation process of a Paleoindian open air site in central Brazil: integrating lithic analysis, radiocarbon and luminescence dating. J Archaeol Sci 40:190–203
Cahen D, Moeyersons J (1977) Subsurface movements of stone artefacts and their implications for the prehistory of Central Africa. Nature 266(5605):812–815
Canti MG (2003) Earthworm activity and archaeological stratigraphy: a review of products and processes. J Archaeol Sci 30(2):135–148
Chamberlain A (2006) Demography in archaeology. Cambridge University Press, Cambridge
Chen K, Harris A, Draskovic J, Schiffer P (2009) Granular fragility under thermal cycles. Granular Matter 11:237–242
Chung YC, Liao HH, Hsiau SS (2013) Convection behavior of non-spherical particles in a vibrating bed: discrete element modeling and experimental validation. Powder Technol 237:53–66
Ciamarra MP, De Vizia MD, Fierro A, Tarzia M, Coniglio A, Nicodemi M (2006) Granular species segregation under vertical tapping: effects of size, density, friction, and shaking amplitude. Phys Rev Lett 96(5):058001
Clarke D (1973) Archaeology: the loss of innocence. Antiquity 47:6–18
Claudin P, Bouchaud J-P (1997) Static avalanches and giant stress fluctuations in silos. Phys Rev Lett 78:231
Dagan Y (2009) Khirbet Qeiyafa in the Judean Shephelah: some considerations. Tel Aviv 36:68–81
Dagan Y (2010) Surveys and excavations along the Cross-Israel Highway. Atiqot 64:3–61
Dahari U, Ad U (1998) Shoham bypass road. Hadashot Arkheologiyot/Excav Surv Israel 108:79–83 **(Hebrew)**
Derkum H, Dietze M (2019) The relevance of diffusion processes for desert pavement dynamics—the experimental view. 21st EGU General Assembly, EGU2019, Proceedings from the conference held 7–12 April, 2019 in Vienna, Austria, id.8107
Dietze M, Bartel S, Lindner M, Kleber A (2012) Formation mechanisms and control factors of vesicular soil structure. CATENA 99:83–96
Dietze M, Kleber A (2012) Contribution of lateral processes to stone pavement formation in deserts inferred from clast orientation patterns. Geomorphology 139–140:172–187
Dietze M, Groth J, Kleber A (2013) Alignment of stone-pavement clasts by unconcentrated overland flow—implications of numerical and physical modelling. Earth Surf Process Landf 38:1234–1243
Dietze M, Dietze E, Lomax J, Fuchs M, Kleber A, Wells SG (2016) Environmental history recorded in aeolian deposits under stone pavements. Quatern Res 85:4–16
Dudill A, Lafaye de Micheaux H, Frey P, Church M (2018) Introducing finer grains into bedload: the transition to a new equilibrium. J Geophys Res: Earth Surf 123:2602–2619
Erlandson JM (1984) A case study in faunal turbation: delineating the effects of the burrowing pocket gopher on the distribution of archaeological materials. Am Antiq 49:785–790
Faust A, Katz H (2012) Survey, shovel tests and excavations at Tel Eton: on methodology and site history. Tel Aviv 39:30–57
Ferdowsi B, Ortiz CP, Houssais M, Jerolmack DJ (2017) River-bed armouring as a granular segregation phenomenon. Nat Commun 8(1363):1–10
Finkelstein I (1996) The Philistine countryside. Israel Explor J 46:225–242
Finkelstein I, Zimhoni O (2000) The pottery from the Late Bronze gate. In: Finkelstein I, Ussishkin D, Halpern B (eds) Megiddo III: the 1992–1996 seasons. Institute of Archaeology, Tel Aviv University, Tel Aviv, pp 223–324
Garfinkel Y, Ganor S (2010) Khirbet Qeiyafa in survey and in excavations: a response to Y. Dagan Tel Aviv 37:67–78
Garzó V (2008) Brazil-nut effect versus reverse Brazil-nut effect in a moderately dense granular fluid. Phys Rev E 78:020301
Gorzalczany A, Baumgarten Y (2005) Horbat Petora (north). Hadashot Arkheologiyot/Excav Surv Israel 117. https://www.hadashotesi.org.il/Report_Detail_Eng.aspx?id=241
Güttler C, von Borstel I, Schräpler R, Blum J (2013) Granular convection and the Brazil nut effect in reduced gravity. Phys Rev E 87:44201
Grotzinger J, Jordan TH (2010) Understanding earth. W.H. Freeman, New York
Hofman JL (1986) Vertical movement of artifacts in alluvial and stratified deposits. Curr Anthropol 27:163–171
Holliday VT (2004) Soils in archaeological research. Oxford University Press, Oxford
Karkanas P, Goldberg P (2018) Reconstructing archaeological sites: understanding the geoarchaeological matrix. Wiley Blackwell, Oxford
Kianian M (2014) Studying surface properties of desert pavements and their relation to soil properties and plant growth in Hajaligholi Playa. Iran Arab J Geosci 7:1457–1461
Kudrolli A (2004) Size separation in vibrated granular matter. Rep Prog Phys 67:209–247
Leibner U (2009) Settlement and history in Hellenistic, Roman, and Byzantine Galilee: an archaeological survey of the Eastern Galilee. Mohr Siebeck, Tübingen
Leigh D (1998) Evaluating artifact burial by eolian vs bioturbation processes, South Carolina Sandhills, USA. Geoarchaeology 13:309–330
Madsen FT, Müller-Vonmoos M (1997) The swelling behaviour of clays. Appl Clay Sci 4(2):143–156
Matsumura S, Richardson DC, Michel P, Schwartz SR, Ballouz R-L (2014) The Brazil nut effect and its application to asteroids. Mon Not R Astron Soc 443(4):3368–3380
Meyn S, Tweedie RL (2009) Markov chains and stochastic stability, 2nd edn. Cambridge University Press, Cambridge
Möbius ME, Lauderdale BE, Nagel SR, Jaeger HM (2001) Brazil-nut effect, size separation of granular particles. Nature 414:270
Moeyersons J (1978) The behaviour of stones and stone implements, buried in consolidating and creeping Kalahari sands. Earth Surf Proc Land 3(2):115–128
Naylor MA, Swift MR, King PJ (2003) Air-driven Brazil nut effect. Phys Rev E 68:012301
Nocita M, Stevens A, van Wesemael B, Aitkenhead M, Bachmann M, Barthès B, Ben Dor E et al (2015) Soil spectroscopy: an alternative to wet chemistry for soil monitoring. Adv Agron 132:139–159
Osborne R (2004) Demography and survey. In: Alcock SE, Cherry JF (eds) Side by side survey: comparative regional studies in the Mediterranean world. Oxbow, Oxford, pp 163–172
Perera V, Jackson AP, Asphaug E, Ballouz R-L (2016) The spherical Brazil nut effect and its significance to asteroids. Icarus 278(1):194–203
Poesen J (1990) Erosion process research in relation to soil erodibility and some implications for improving soil quality. In: Albaladejo J, Stocking MA, Diaz E (eds) Soil degradation and rehabilitation

in Mediterranean environmental conditions. C.S.I.C, Madrid, pp 159–170
Poesen J, Lavee H (1994) Rock fragments in top soils: significance and processes. CATENA 23:1–28
Poesen J, van Wesemael B, Govers G, Martinez-Fernandez J, Desmet P, Vandaele K, Quine T, Degraer G (1997) Patterns of rock fragment cover generated by tillage erosion. Geomorphology 18:183–197
Portugali J (1982) A field methodology for regional archaeology (the Jezreel Valley survey, 1981). Tel Aviv 9:170–188
Postgate N (1994) How many Sumerians per hectare? Probing the anatomy of an early city. Cambridge Archaeol J 4:47–65
Ravikovitch S (1981) The soils of Israel, formation, nature and properties. Hakibbutz Hameuchad, Tel Aviv **(Hebrew)**
Rémond S (2004) Compaction of confined mono-sized spherical particle systems under symmetric vibration: a suspension model. Phys A 337(3–4):411–427
Rosato A, Blackmore DL, Zhang N, Lan Y (2002) A perspective on vibration-induced size segregation of granular materials. Chem Eng Sci 57:265–275
Rosato A, Strandburg KJ, Prinz F, Swendsen RH (1987) Why the Brazil nuts are on top: Size segregation of particulate matter by shaking. Phys Rev Lett 58(10):1038–1040
Rowlett RM, Robbins MC (1982) Estimating original assemblage content to adjust for post-depositional vertical artifact movement. World Archaeol 14:73–83
Sapir Y, Faust A (2016) Utilizing mole-rat activity for archaeological survey: a case study and a proposal. Adv Archaeol Pract 4:55–70
Schiffer MB (1972) Archaeological context and systemic context. Am Antiq 37(2):156–165
Schiffer MB (1983) Toward the identification of formation processes. Am Antiq 48(4):675–706
Schiffer MB (1985) Is there a "Pompeii premise" in archaeology? J Anthropol Res 41(1):18–41
Schiffer MB (1987) Formation processes of the archaeological record. University of New Mexico Press, Albuquerque
Schiffer MB (2010) Behavioral archaeology: principles and practice. Equinox, London
Schnautz T, Brito R, Kruelle CA, Rehberg I (2005) A horizontal Brazil-nut effect and its reverse. Phys Rev Lett 95:028001
Schröter M, Ulrich S, Kreft J, Swift JB, Swinney HL (2006) Mechanisms in the size segregation of a binary granular mixture. Phys Rev E 74(1):011307
Seil P, Pirker S, Lichtenegger T (2018) Onset of sediment transport in mono- and bidisperse beds under turbulent shear flow. Comput Part Mech 5(2):203–212
Shai I, Uziel J (2014) Addressing survey methodology in the southern Levant: applying different methods for the survey of Tel Burna, Israel. Israel Explor J 64:172–190
Shavit A, Wolf S (2008) Hamid, Tel. In: Stern E (ed) The new encyclopedia of archaeological excavations in the Holy Land, vol 5. Israel Exploration Society, Jerusalem, pp 1762–1763
Shinbrot T (2004) Granular materials: the Brazil nut effect—in reverse. Nature 429:352–353
Shinbrot T, Muzzio FJ (2000) Nonequilibrium patterns in granular mixing and segregation. Phys Today 53(3):25–30
Shott M (1985) Shovel-test sampling as a site discovery technique: a case study from Michigan. J Field Archaeol 12:457–468
Staurset S, Coulson S (2014) Sub-surface movement of stone artefacts at white paintings shelter, Tsodilo Hills, Botswana: implications for the middle stone age chronology of central Southern Africa. J Hum Evol 75:153–165
Stein JK (1983) Earthworm activity: a source of potential disturbance of archaeological sediments. Am Antiq 48:277–289
Stein JK (2001) A review of site formation processes and their relevance to geoarchaeology. In: Holliday P, Goldberg VT, Reid Ferring C (eds) Earth sciences and archaeology. Springer, New York, pp 37–48
Stoner ER, Baumgardner MF, Biehl LL, Robinson BF (1980) Atlas of soil reflectance properties. Purdue University, West Lafayette
Sullivan AP (1978) Inference and evidence in archaeology: a discussion of the conceptual problems. Adv Archaeol Method Theory 1:183–222
Sullivan AP, Dibble WF (2014) Site formation processes. In: Smith C (ed) Encyclopedia of global archaeology. Springer, New York. https://doi.org/10.1007/978-1-4419-0465-2_211
Tariq A, Durnford DS (1993) Analytical volume change model for swelling clay soils. Soil Sci Soc Am J 57:1183–1187
Tartaron TF (2003) The archaeological survey: sampling strategies and field methods. Hesperia Suppl 32:23–45
Valentine GA, Harrington CD (2006) Clast size controls and longevity of Pleistocene desert pavements at Lathrop Wells and Red Cone volcanoes, Southern Nevada. Geology 34:533–536
Villa P (1982) Conjoinable pieces and site formation processes. Am Antiq 47:276–290
Villa P, Courtin J (1983) The interpretation of stratified sites: a view from underground. J Archaeol Sci 10(3):267–281
Viscarra Rossel RA, Behrens T, Ben-Dor E et al (2016) A global spectral library to characterize the world's soil. Earth Sci Rev 155:198–230
Viscarra Rossel RA, Bouma J (2016) Soil sensing: a new paradigm for agriculture. Agric Syst 148:71–74
Wang Z, Miles NJ, Wu T, Gu F, Hall P (2016) Recycling oriented vertical vibratory separation of copper and polypropylene particles. Powder Technol 301:694–700
Wells SG, McFadden LD, Poths J, Olinger CT (1995) Cosmogenic 3He surface-exposure dating of stone pavements; implications for landscape evolution in deserts. Geology 23:613–616
Whallon R (1979) An archaeological survey of the Keban reservoir area of east-central Turkey. University of Michigan Press, Ann Arbor
Więckowski W, Cohen S, Mienis HK, Kolska Horwitz L (2013) The excavation and analysis of porcupine dens and burrowing on ancient and recent faunal and human remains at Tel Zahara (Israel). Bioarchaeol Near East 7:3–20
Williams JC, Shields G (1967) The segregation of granules in a vibrated bed. Powder Technol 1(3):134–142
Wood WR, Johnson DL (1978) A survey of disturbance processes in archaeological site formation. Adv Archaeol Method Theory 1:315–381
Wossink A (2009) Challenging climate change: competition and cooperation among pastoralists and agriculturalists in Northern Mesopotamia (c. 3000–1600 BC). Sidestone Press, Leiden
Xu C, Zhu J (2006) Parametric study of fine particle fluidization under mechanical vibration. Powder Technol 161(2):135–144
Yaalon DH (1997) Soils in the Mediterranean region: what makes them different? CATENA 28:157–169
Yaalon DH, Ganor E (1973) The influence of dust on soils during the Quaternary. Soil Sci 116:146–155
Yaalon DH, Kalmar D (1978) Dynamics of cracking and swelling clay soils: displacement of skeletal grains, optimum depth of slickensides, and rate of intra-pedonic turbation. Earth Surf Process 3:31–42